A 3D visualization of a particle collision. A central purple cylindrical structure is surrounded by yellow and green components. A bright orange starburst of lines radiates from the center, representing the collision point. The background is a dark blue, curved structure, possibly a detector or accelerator component.

LATTICE FIELD THEORY AT THE ENERGY FRONTIER

Anna Hasenfratz
University of Colorado

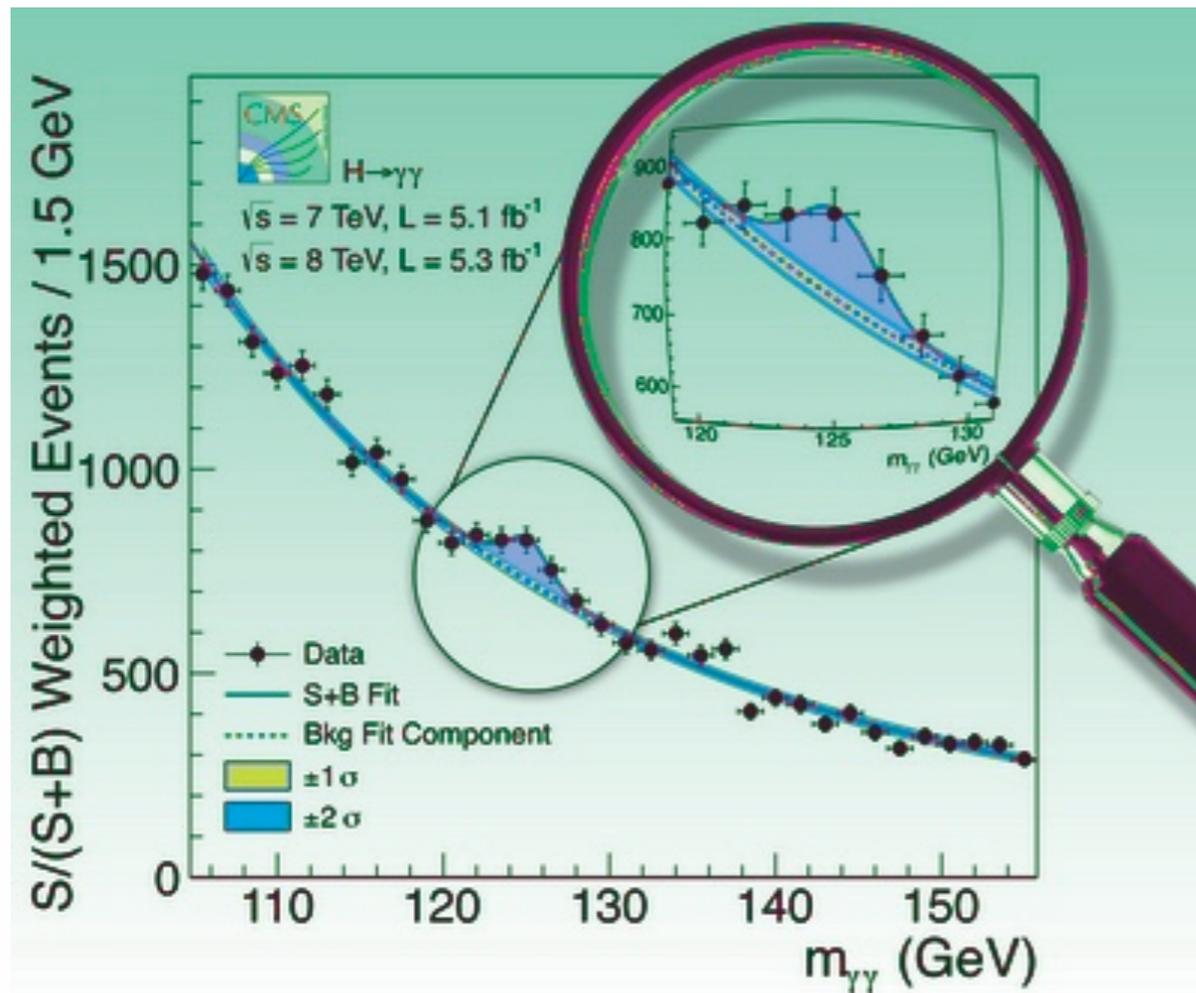
USQCD Hardware Review, BNL, May 21-22, 2015

Run: 264034
Event: 11526514
2015-05-06 22:54:50

proton-proton collisions at
900 GeV centre-of-mass energy

Higgs era of particle physics

The 2012 discovery of the Higgs boson completed the Standard Model



Yet puzzles remain -
The SM

- requires fine-tuning
- has nearly 20 parameters
- does not explain origin of EW symmetry breaking, neutrinos, dark matter,...

What is the correct Beyond-SM extension?

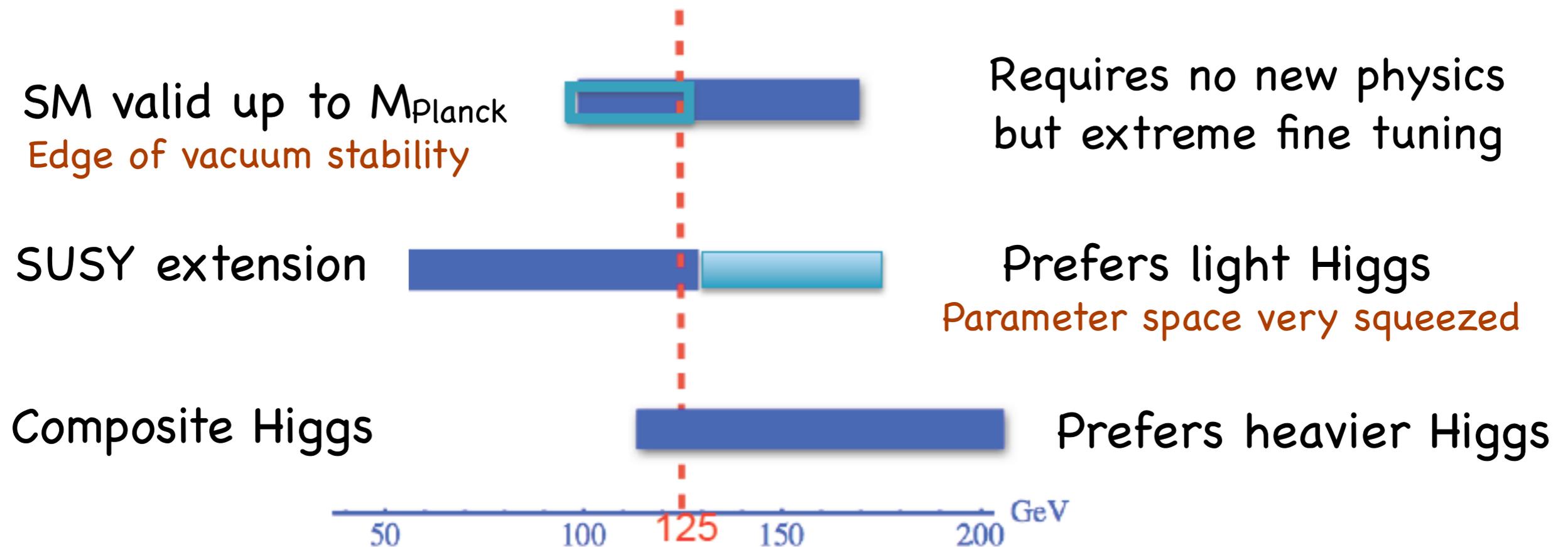
Search is driven by the puzzles,
confirmed by experiments

Possible BSM models

a few popular options ...

blue bands represent typical ranges for Higgs mass

(Marcela Carena)



New symmetries are needed to stabilize a scalar against (quadratic) UV divergences (below the Planck mass).

Composite Higgs models

Two recent papers investigating composite Higgs at the LHC:

Fundamental Composite Electroweak Dynamics: Status at the LHC

Alexandre Arbey,^{a,b,c} Giacomo Cacciapaglia,^d Haiying Cai,^d Aldo Deandrea,^{d,1} Solène Le Corre,^b Francesco Sannino^e

ArXiv:1502.04718

Search for a new resonance decaying to a W or Z boson and a Higgs boson in the $\ell\ell/\ell\nu/\nu\nu + b\bar{b}$ final states with the ATLAS Detector

The ATLAS Collaboration

ArXiv:1503.08089

Collaborative effort

There are composite models that viable, but they are strongly coupled

-> lattice calculations are necessary

For significant impact, collaboration between

- model builders
- lattice practitioners

is needed to explore and understand BSM systems

Lattice for Beyond the Standard Model Physics

HIGH PERFORMANCE COMPUTING
INNOVATION CENTER
YOSEMITE CONFERENCE AUDITORIUM

APRIL 23-25, 2015

LAWRENCE LIVERMORE
NATIONAL LABORATORY
OPEN CAMPUS
LIVERMORE, CALIFORNIA



SPONSORED BY LAWRENCE LIVERMORE NATIONAL LABORATORY

Focus:

[LLNL workshop](#)

The focus will be on the **role that Lattice numerical simulations can play** in the study of possible strong interactions in **Beyond the Standard Model (BSM) physics**, and in particular within the following topic areas:

- Composite dark matter
- Composite Higgs models and EWSB
- Theoretical applications in conformal field theory, string theory, and holography
- Strongly coupled models, including many-fermion gauge theories and SUSY

Half of the talks and the participants were non-lattice

Lattice BSM workshops

Sakata Memorial KMI Mini-Workshop on
"Strong Coupling Gauge Theories Beyond the Standard Model"
(SCGT14Mini)



March 5 (Wednesday) - March 7 (Friday), 2014

Science Symposia (ES 635), 6th Floor of ES Building
Kobayashi-Maskawa Institute for the Origin of Particles and the Universe (KMI)
Nagoya University, Nagoya, Japan

<http://www.SCGT14Mini/>

Topics

- LHC Phenomenology of the Walking Technicolor
- Lattice Studies of Conformal Strong Dynamics
- String and Holographic View of Strong Coupling Gauge Theories
- Composite Models for Higgs and others
- Dilaton and Conformal Symmetry in Strong Coupling Gauge Theories
- Other Related Topics

Sakata Memorial KMI Workshop on
"Origin of Mass and Strong Coupling Gauge Theories"
(SCGT15)



March 3 (Tuesday) - March 6 (Friday), 2015

Sakata-Hirata Hall, Nagoya University, Nagoya, Japan

<http://www.SCGT15/>

The purpose of this workshop is to discuss theoretical and phenomenological issues of strong coupling gauge theories as well as those in extreme conditions, particularly in view of the new phase of the LHC experiments and the conformal fixed point for the gauge/gravity. Synergy of the lattice, string and phenomenological studies at the meeting will be extremely important in this phase of the particle physics.

Shoichi Sakata at Nagoya University proposed in 1956 the Sakata model, a composite model for hadrons, which paved a

Lattice Meets Experiment 2013: BEYOND THE STANDARD MODEL

RIKEN BNL Research Center Workshop
December 5-6, 2013 at Brookhaven National Laboratory

[Homepage](#) [Registration](#) [Agenda](#) [Contact Us](#) [Workshop Information](#)

Lattice Meets Experiment 2013: Beyond the Standard Model

Co-sponsored by [USQCD](#)

<http://www.bnl.gov/lme2013/>

Motivation

Lattice gauge theory, which is an active field of research at RBRC and BNL, provides a rigorous, numerical approach to the study of particle physics models in strongly-coupled regimes. In addition to the study of the strong nuclear force as described by quantum chromodynamics (QCD), lattice studies can play an important role in many areas of research into possible new physics beyond the Standard Model (BSM), including:

- Intersections between new physics and QCD, such as proton decay and electric dipole

PPCM

Field Theoretic Computer Simulations for Particle Physics and Condensed Matter

[PPCM](#) [SCHEDULE](#) [POSTER SIGNUP](#) [PARTICIPANTS](#) [TRAVEL & HOTEL](#)

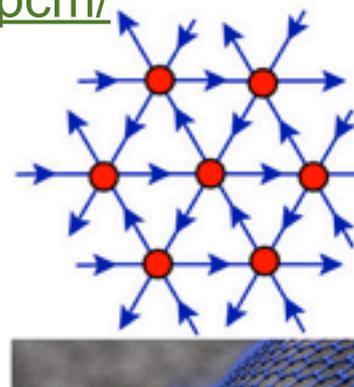
PPCM

FIELD THEORETIC COMPUTER SIMULATIONS
FOR PARTICLE PHYSICS AND CONDENSED MATTER

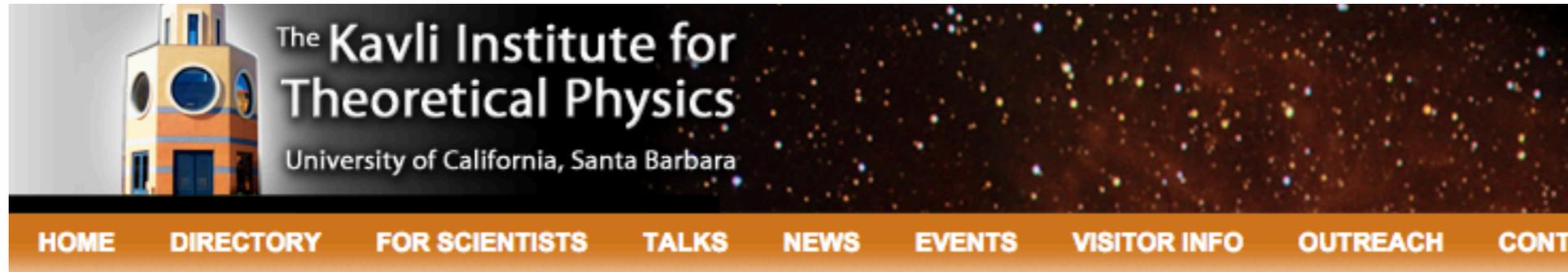
8-10 MAY 2014
BOSTON UNIVERSITY CENTER FOR COMPUTATIONAL SCIENCE

This 2.5-day workshop is devoted to common problems in the theoretical and computational study of particle physics and condensed matter. It will take place from Thursday, 8 May, through Saturday morning, 10 May 2014, at the Boston

<http://blogs.bu.edu/ppcm/>



Lattice BSM workshops



Lattice Gauge Theory for the LHC and Beyond

Coordinators: Simon Catterall, Anna Hasenfratz, Andreas Kronfeld, Yannick Meurice

Scientific Advisors: Csaba Csaki, Adam Martin, Ann Nelson, Erich Poppitz, Robert Sugar <http://www.kitp.ucsb.edu/>

This program will focus on the uses of lattice gauge theory to explore particle physics beyond the Standard Model. Within this broad theme, we aim to integrate three main subtopics: tests of the Standard Model in quark flavor physics, fundamental probes of new physics at the interface of nuclear and particle physics, and nonperturbative phenomena in electroweak symmetry breaking.



May 24 - June 14

Understanding Strongly Coupled Systems in High Energy and Condensed Matter Physics

Organizers:

Richard Brower, Boston University

Simon Catterall, Syracuse University

Shailesh Chandrasekharan*, Duke University

Anders W. Sandvik, Boston University

Richard Scalettar, University of California, Davis

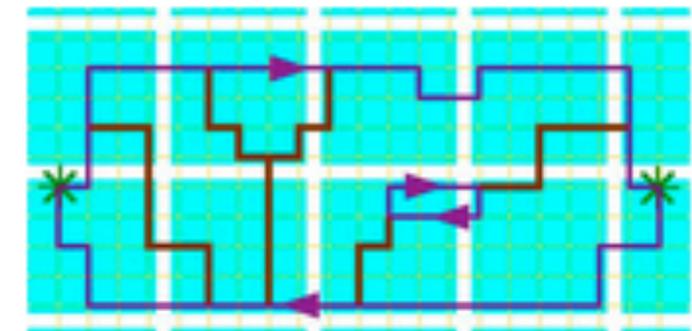
Uwe-Jens Wiese, CERN

Lattice Gauge Theory Simulations Beyond the Standard Model of Particle Physics

Location : CECAM-ISR, Tel Aviv University, Israel

June 22, 2015 - June 26, 2015

- Benjamin Svetitsky
Tel Aviv University, Israel
- Maria Paola Lombardo
INFN, Italy
- Kari Rummukainen
University of Helsinki, Finland
- Tomer Volansky
Tel Aviv University, Israel



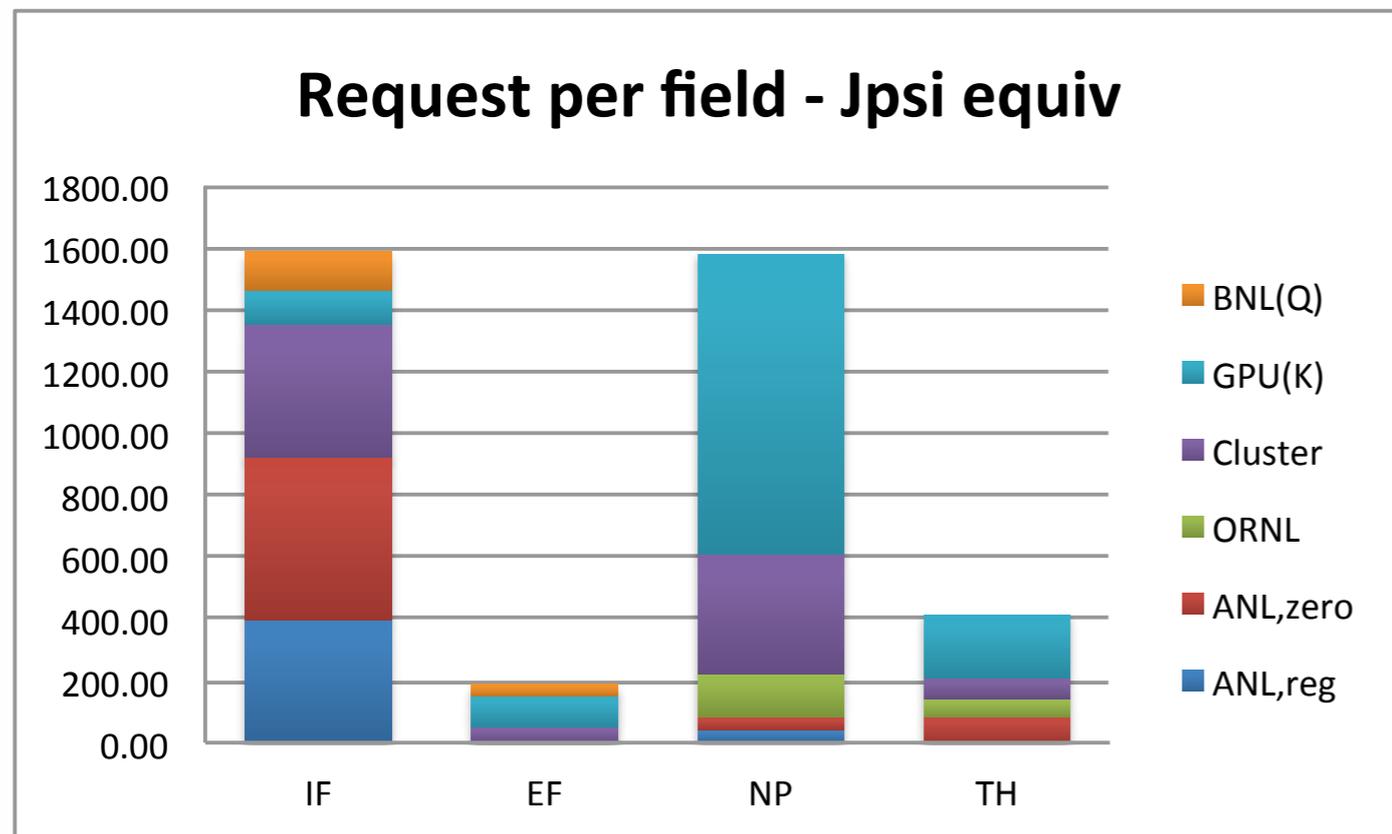
<http://www.cecarn.org/workshop-1128.html>

<http://www.aspenphys.org//currentworkshops.html>

BSM within USQCD

BSM groups work on a wide variety of topics but use only about 10% of USQCD resources

Our projects are more exploratory and frequently smaller than other HEP and NP projects



2015 requests:

BSM is 9% of total

See talk by Paul Mackenzie

Even with limited resources there were 37 publication from USQCD-USBSM in 2014-15

Science Highlights

Very brief summary
of some recent results
from the USQCD-USBSM community

Composite Higgs models

What is the mechanism that keeps the Higgs light?

Spontaneously broken symmetry \rightarrow massless Goldstone bosons

- **Scale symmetry:** SSB leads to dilaton: **near-conformal models**
- **Flavor symmetry:** SSB leads to massless "pions"

What are the general properties these models?

- spectrum, scalar mass, decay constants, etc

Do the BSM models satisfy EW constraints?

- S parameter, WW scattering

Dark matter candidates and properties

Near-conformal systems

Boulder-Boston (→ LSD collaboration):

An $SU(3)$ model with $N_l=4$ light (massless) and $N_h=8$ heavy fermions interpolates between

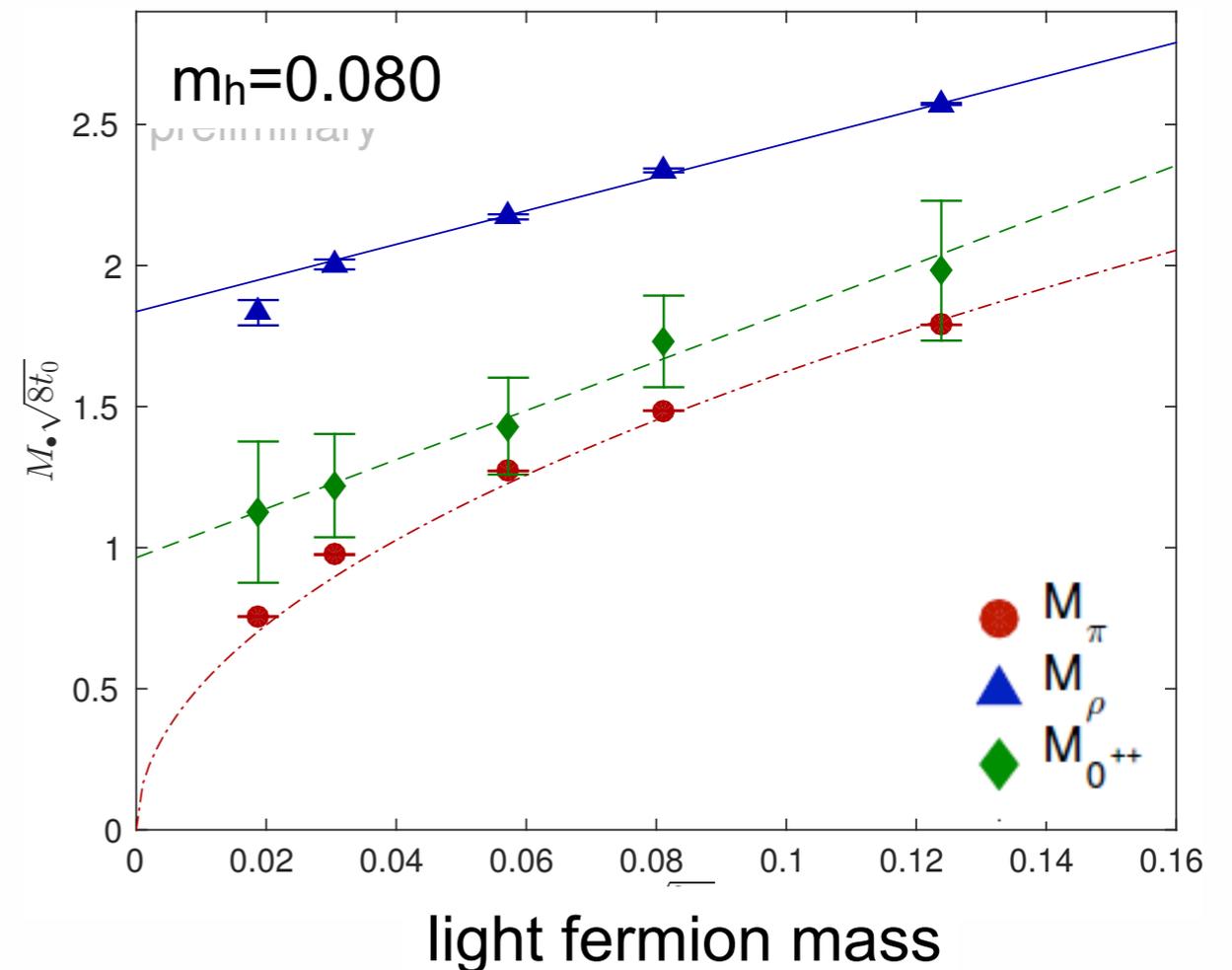
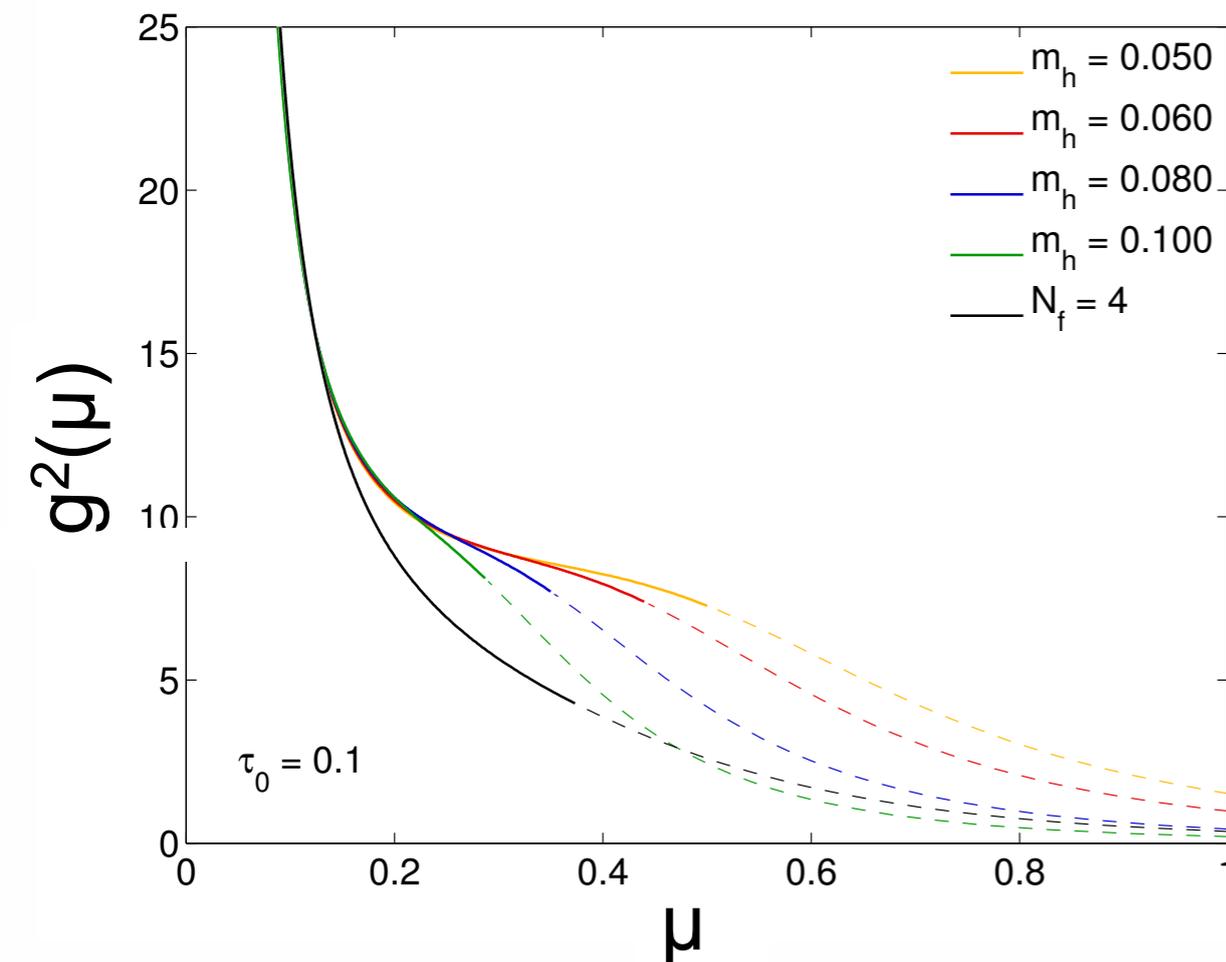
- conformal behavior when $m_h \sim m_l$
($N_f=12$ is conformal)
- chiral symmetry breaking when $m_h \gg m_l$
($N_f=4$ is chirally broken)

By tuning the mass of the 8 heavy flavors $m_h \rightarrow m_l$
study the emergence of a light dilaton as Higgs candidate

SU(3), 4+8 flavors

The running coupling shows
“walking”

Spectrum: 0^{++} scalar is light
→ it is a Higgs candidate



4+8 flavor study shows that it is possible to construct models that exhibit behavior needed for realistic BSM

SU(3) gauge, 2-flavor sextet

Lattice Higgs Collaboration :

This model is a favored composite Higgs candidate

- if chirally broken it has 3 Goldstone bosons:
ideal for EW symmetry breaking
- one of the models considered by the ATLAS collaboration

Search for a new resonance decaying to a W or Z boson and a Higgs boson in the $\ell\ell/\ell\nu/\nu\nu + b\bar{b}$ final states with the ATLAS Detector



Submitted to: Eur. Phys. J. C.

References

- [1] ATLAS Collaboration, *Phys.Lett.* **B716** (2012) 1–29, [arXiv:1207.7214 \[hep-ex\]](#).
- [2] CMS Collaboration, *Phys.Lett.* **B716** (2012) 30–61, [arXiv:1207.7235 \[hep-ex\]](#).
- [3] Particle Data Group Collaboration, K. Olive et al., *Chin.Phys.* **C38** (2014) 090001.
- [4] K. G. Wilson, *Phys.Rev.* **D3** (1971) 1818.
- [5] F. Sannino and K. Tuominen, *Phys.Rev.* **D71** (2005) 051901, [arXiv:hep-ph/0405209 \[hep-ph\]](#).

The ATLAS Collaboration



CERN-PH-EP-2015-052
30th March 2015

- [12] Fodor, Z. et al., *Phys.Lett.* **B718** (2012) 657–666, [arXiv:1209.0391 \[hep-lat\]](#).
- [13] Z. Fodor, K. Holland, J. Kuti, D. Nogradi, and C. H. Wong, *PoS LATTICE2013* (2014) 062, [arXiv:1401.2176 \[hep-lat\]](#).
- [14] A. Hietanen, R. Lewis, C. Pica, and F. Sannino, *JHEP* **1407** (2014) 116, [arXiv:1404.2794 \[hep-lat\]](#).

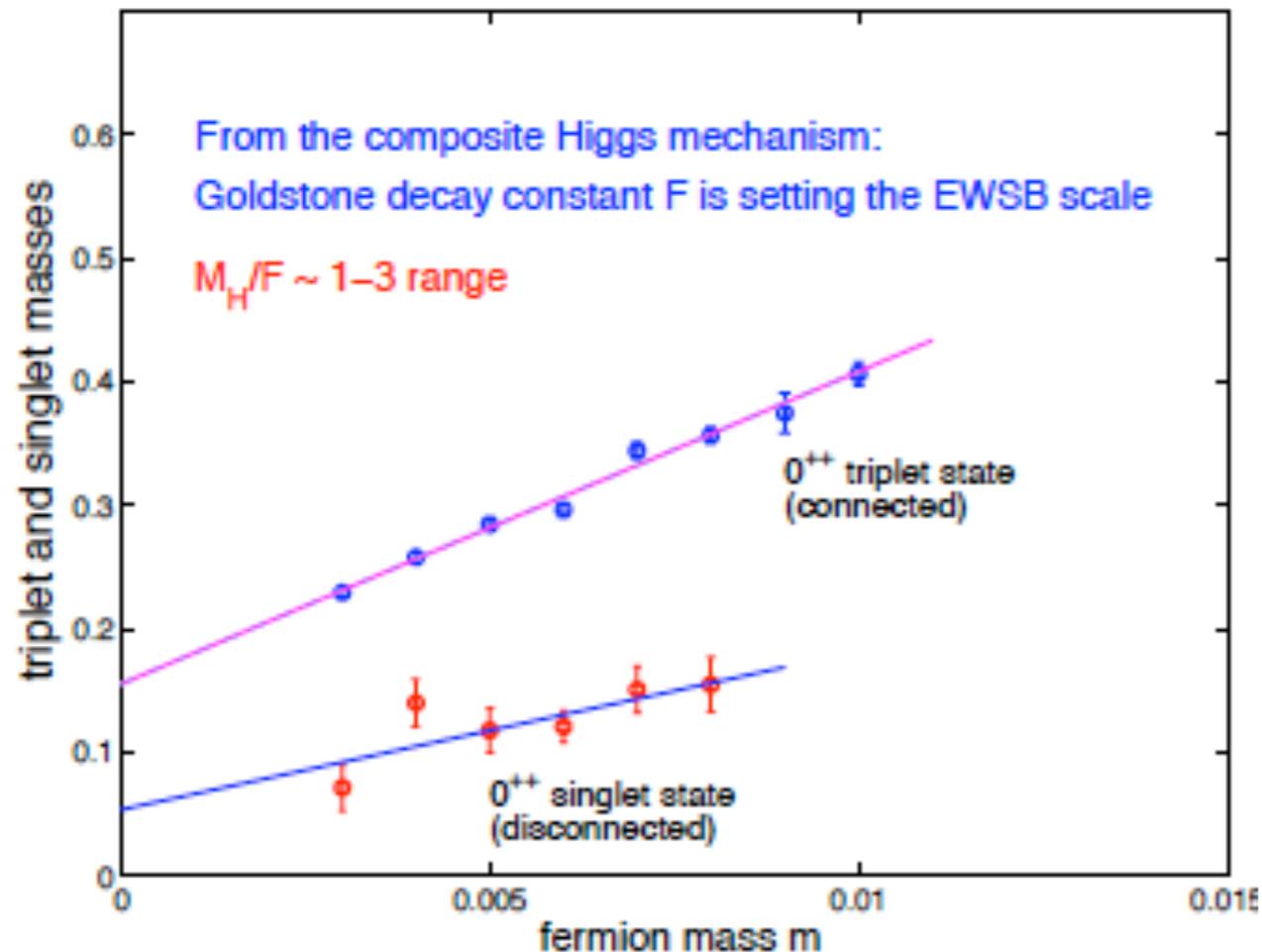
SU(3) 2-flavor sextet

0^{++} is light

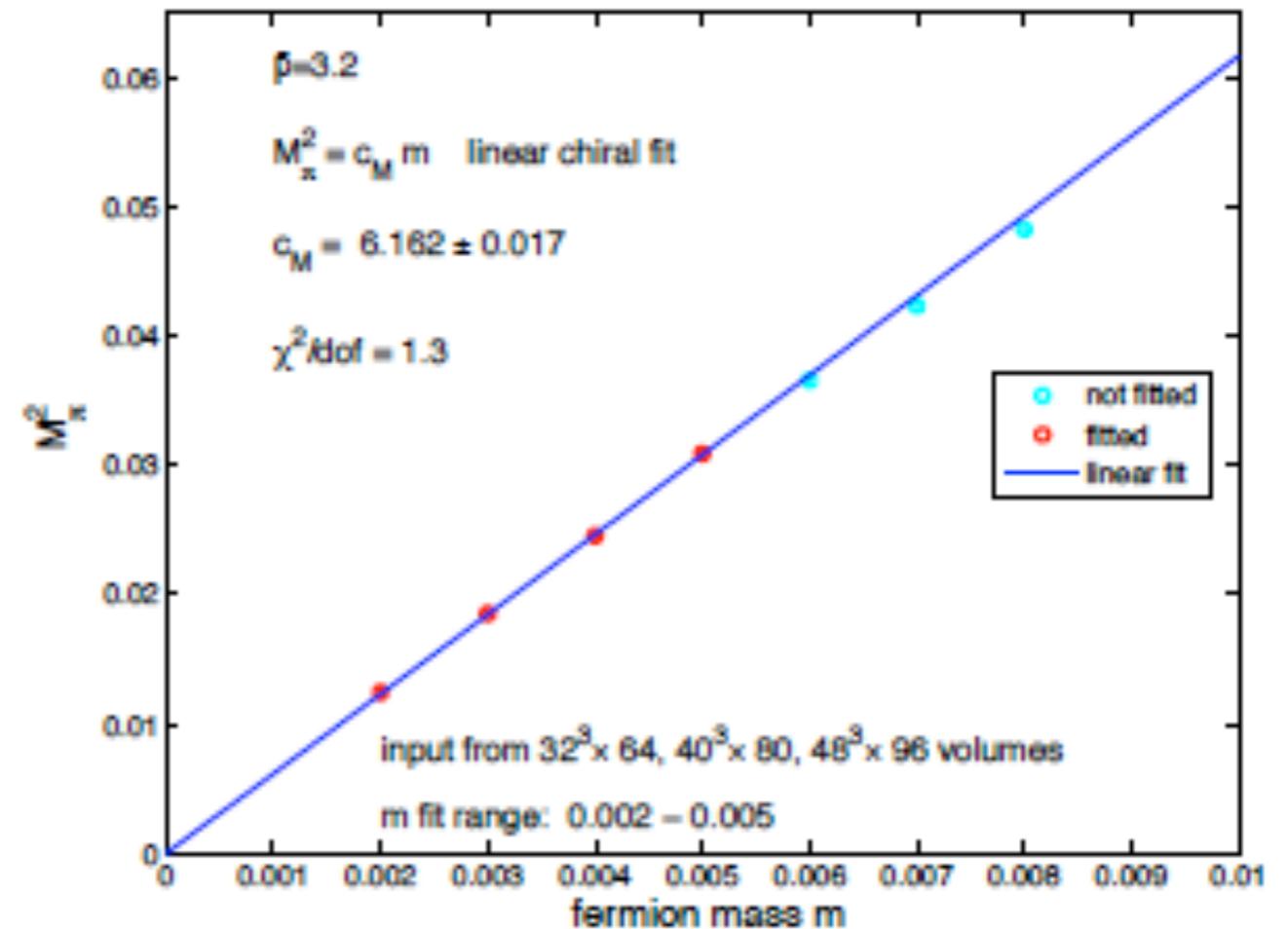
arXiv:1502:00028

- lighter than the pion in the investigated range

Triplet and singlet masses from 0^{++} correlators



Goldstone pion (Rwall pion channel)



It will be very interesting to see the chiral limit

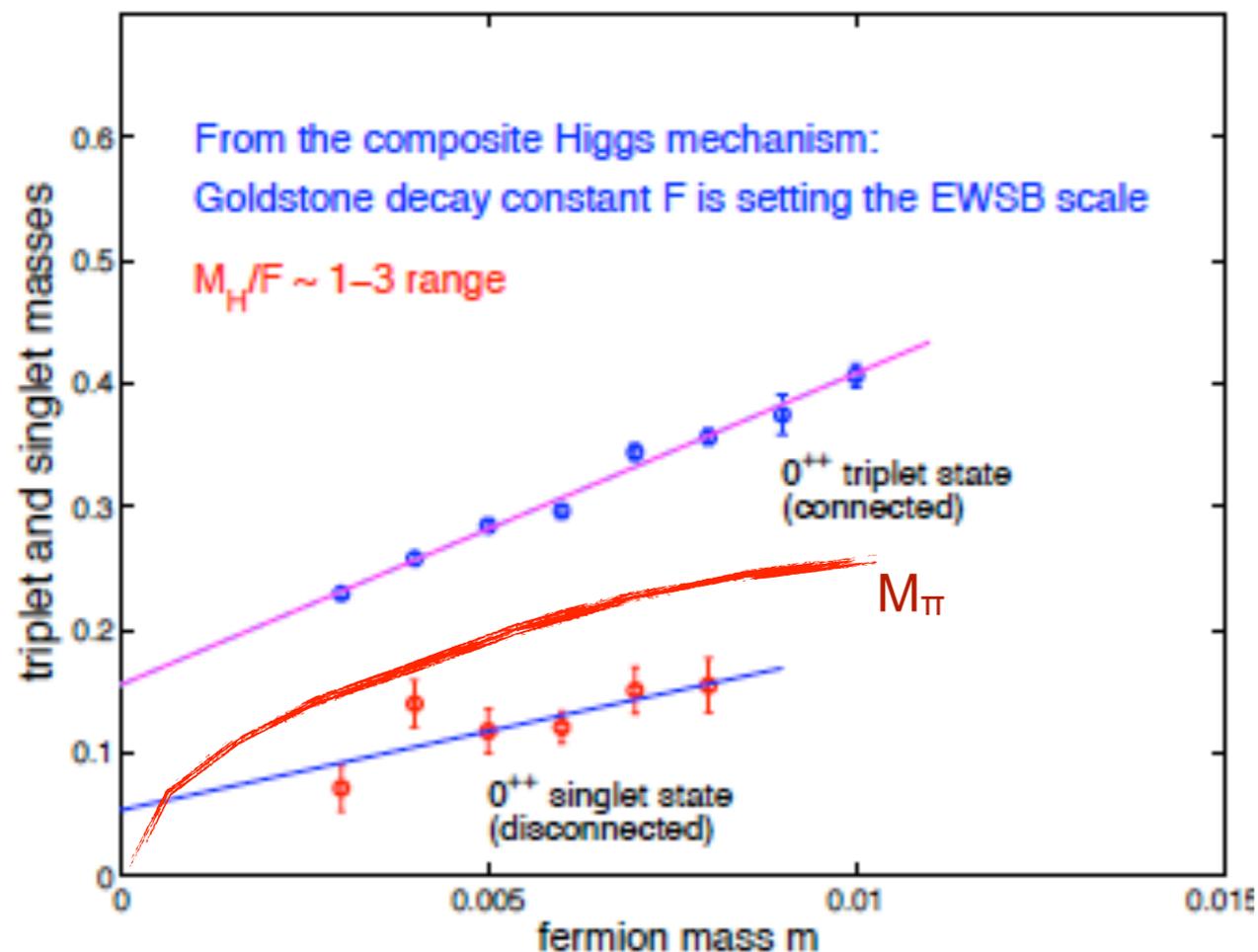
SU(3) 2-flavor sextet

0^{++} is light

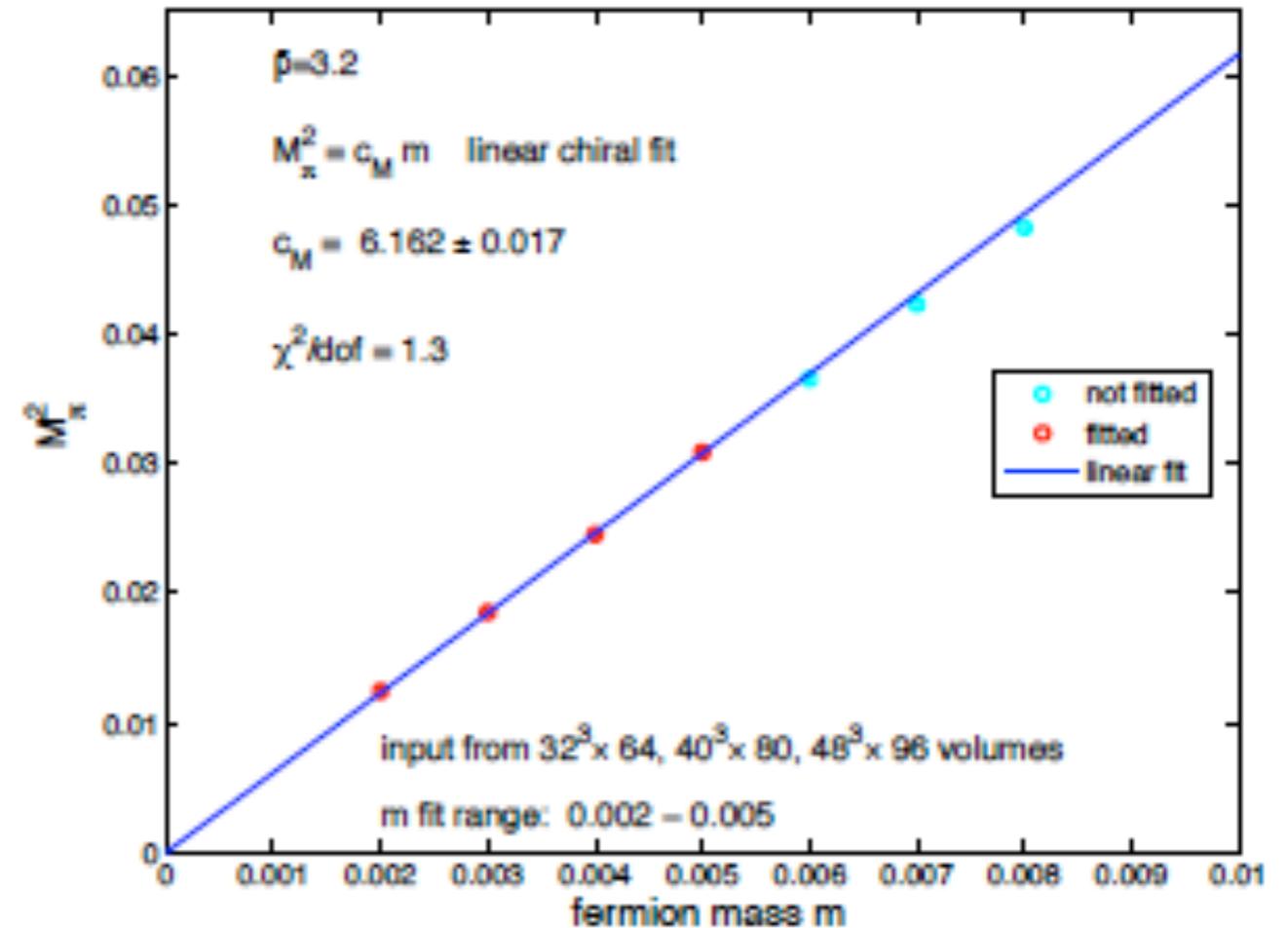
arXiv:1502:00028

- lighter than the pion in the investigated range

Triplet and singlet masses from 0^{++} correlators



Goldstone pion (Rwall pion channel)



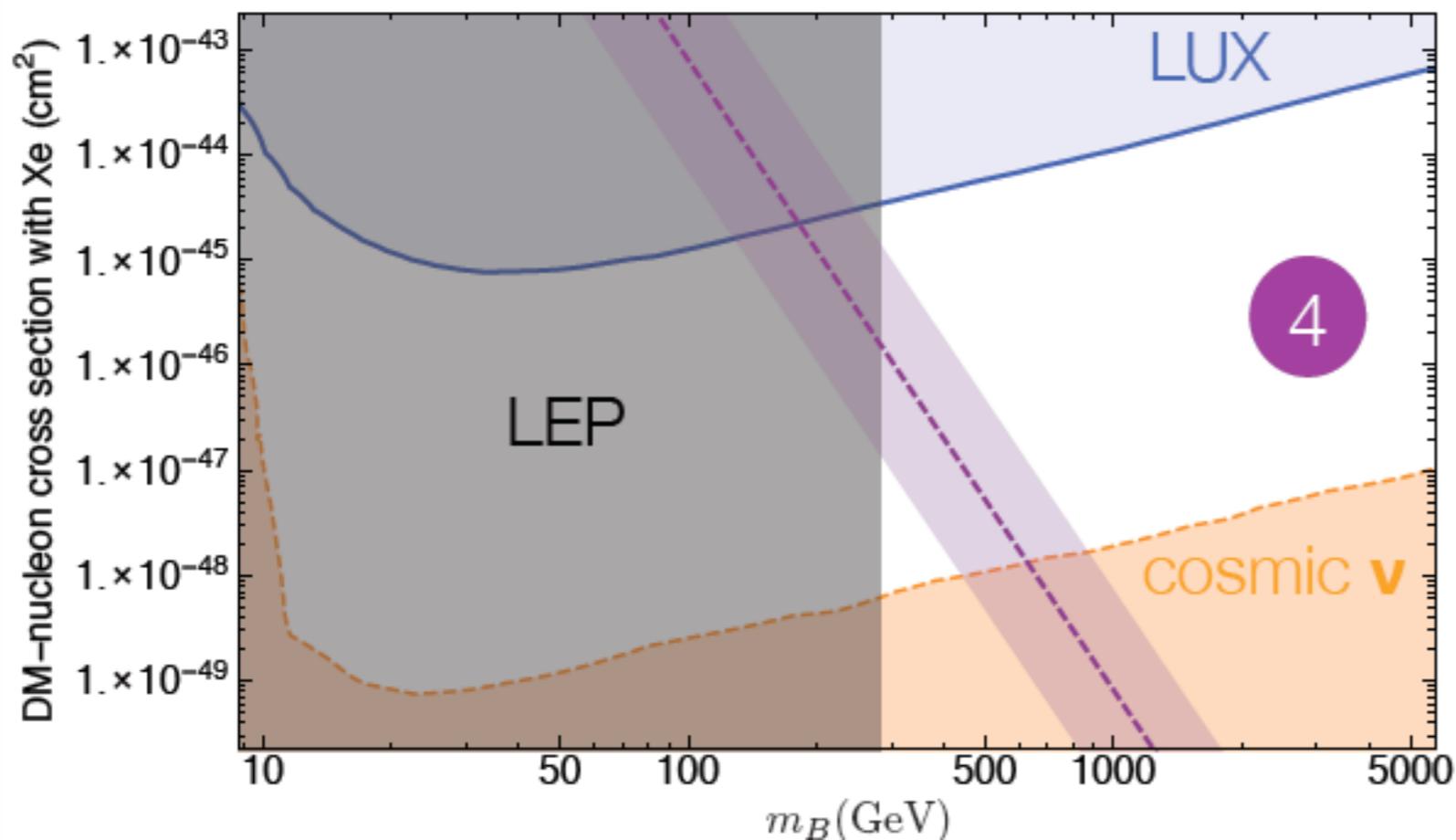
It will be very interesting to see the chiral limit

Dark Matter

Composite Higgs models have dark matter candidates
General properties can be investigated in simple models

LSD collaboration: Stealth dark matter

Custodial symmetry in $SU(4)$ gauge model guarantees that DM interacts with SM only through EM polarizability



Lattice calculations of DM-nucleon cross section reveal a window of discovery up to $\sim 1\text{TeV}$

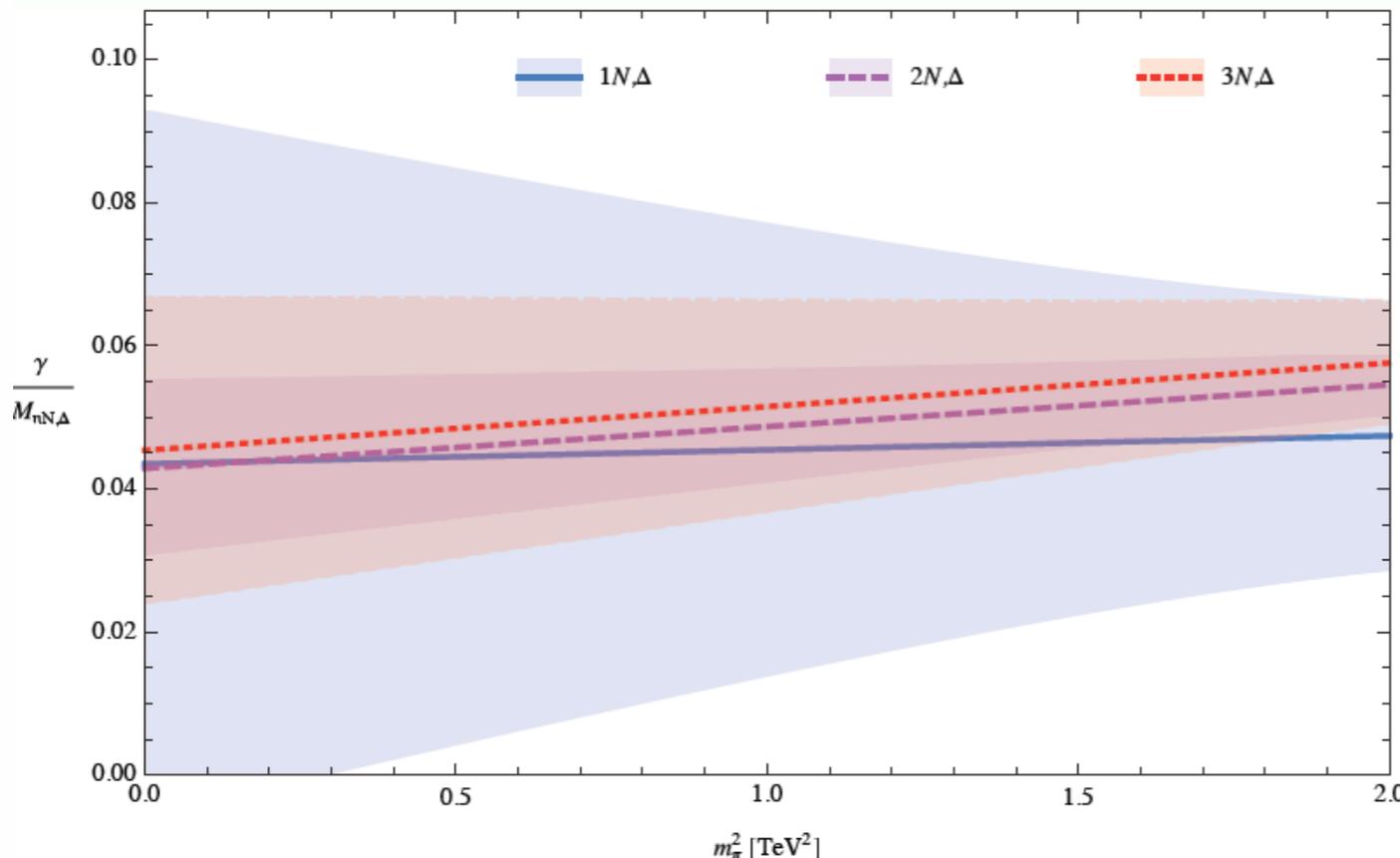
This DM is EW charged
→ novel collider pheno

Dark Matter

MIT group: Dark nuclei

- Could dark nucleons form bound states?
- How does the existence of dark nuclear matter change DM phenomenology?

Lattice calculation with $SU(2)$ gauge + fundamental fermions show that bound states could be quite general



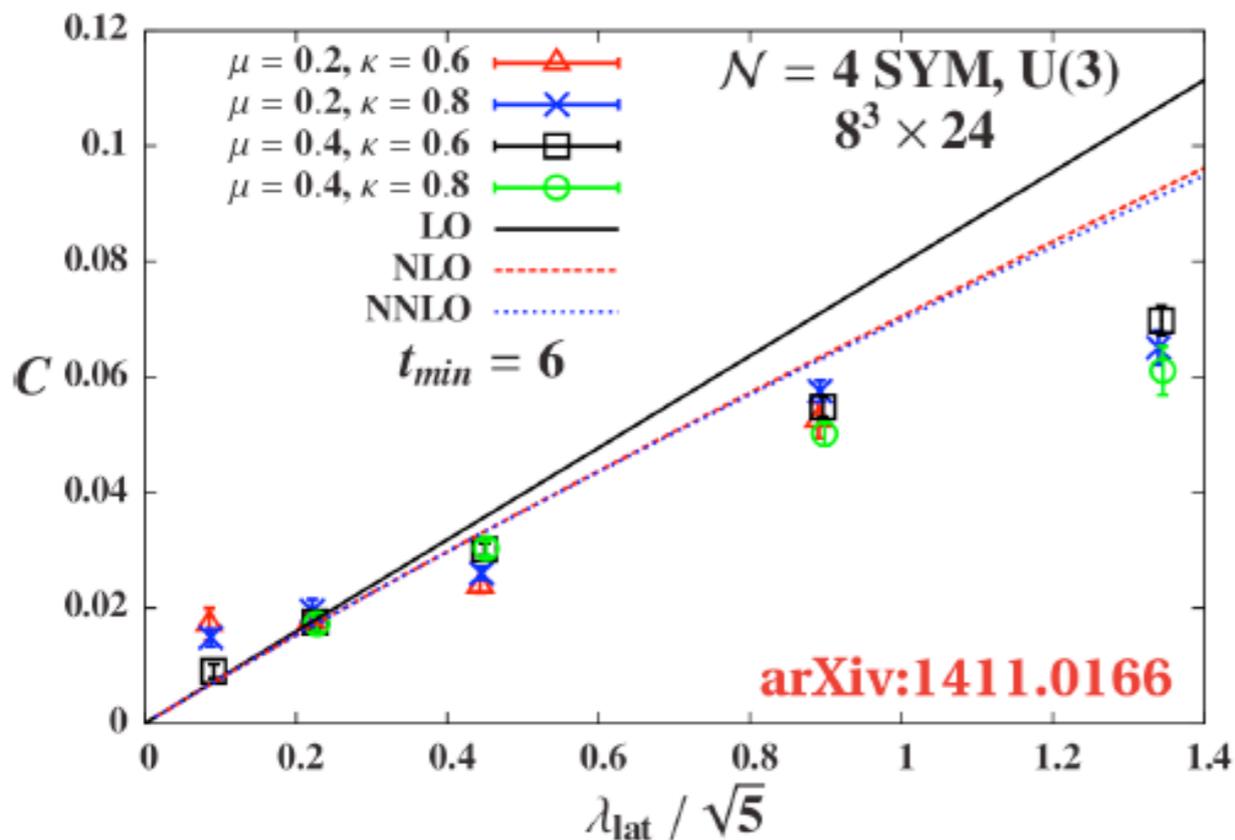
J=1 states with B=2,3,4 appear bound

Lattice Supersymmetry

Lat-SUSY group

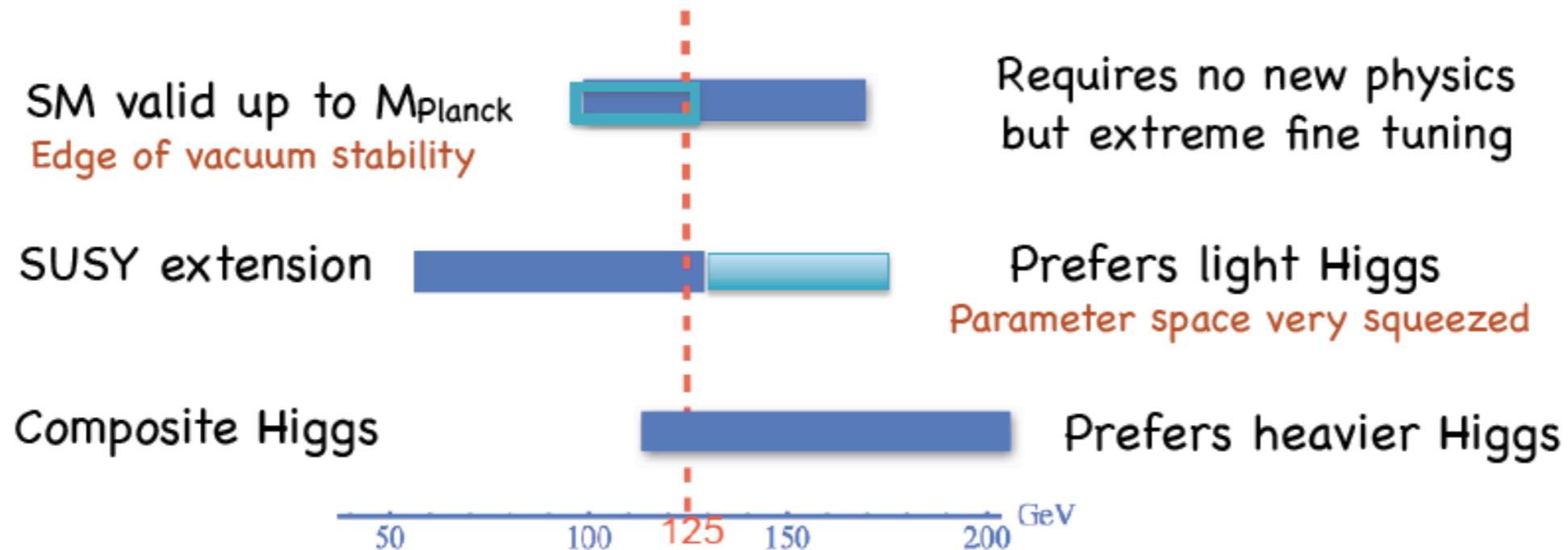
$\mathcal{N}=4$ Super-Yang-Mills: cornerstone of ADS/CFT,
lattice results are important for continuum theorists

- Efficient parallel code developed & optimized
publicly available <https://github.com/daschaich/susy>
- Recent theory work on improved action lead to ~500
reduction in lattice artifacts



Results on the static potential
suggests approach towards strong
coupling ADS/CFT prediction

Where do we go from here?



If LHC finds sign of possible compositeness, lattice investigations will be essential to identify the correct model and study its properties

Study of strongly coupled QFTs is important: Dark matter, condensed matter, electroweak symmetry breaking

Summary

Lattice calculations at the energy frontier investigate
Beyond-Standard Model extensions:

- close work with model builders, experimentalists
- lattice is needed in strongly coupled systems
- first results show near-conformal systems can have needed properties:
 - walking gauge coupling
 - large mass anomalous dimension
 - light 0^{++} state

Many new directions are at early stages: results are expected at the same time as new LHC runs.

37 Publications in 2014-15

1) [The running coupling of 8 flavors and 3 colors.](#)

By Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong.
[arXiv:1503.01132 [hep-lat]].

2) [Toward the minimal realization of a light composite Higgs.](#)

By Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong.
[arXiv:1502.00028 [hep-lat]].

3) [Baryon spectrum in the composite sextet model.](#)

By Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong.
[arXiv:1501.06607 [hep-lat]].

4) [The lattice gradient flow at tree level.](#)

By Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong.
[arXiv:1410.8801 [hep-lat]].

5) [The lattice gradient flow at tree-level and its improvement.](#)

By Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong.
[arXiv:1406.0827 [hep-lat]].

[10.1007/JHEP09\(2014\)018.](#)

JHEP 1409 (2014) 018.

6) [The Higgs particle and the lattice.](#)

By Julius Kuti.

PoS LATTICE2013 (2014) 004.

7) [Can the Higgs Impostor Hide Near the Conformal Window?.](#)

By Zoltán Fodor, Kieran Holland, Julius Kuti, Dániel Nógrádi, Christopher Schroeder, Chik Him Wong.

[10.1142/9789814566254_0002.](#)

8) [The chiral condensate from the Dirac spectrum in BSM gauge theories.](#)

By Zoltán Fodor, Kieran Holland, Julius Kuti, Dániel Nógrádi, Chik Him Wong.

[arXiv:1402.6029 [hep-lat]]. PoS LATTICE2013 (2014) 089.

9) [Can a light Higgs impostor hide in composite gauge models?.](#)

By Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong.

[arXiv:1401.2176 [hep-lat]]. PoS LATTICE2013 (2014) 062.

10) [Models of Walking Technicolor on the Lattice.](#)

By D.K. Sinclair, J.B. Kogut. [arXiv:1410.8494 [hep-lat]].

11) [Thermodynamics of lattice QCD with 3 flavours of colour-sextet quarks II. \$N_t=6\$ and \$N_t=8\$.](#)

By J.B. Kogut, D.K. Sinclair. [arXiv:1406.1524 [hep-lat]].

[10.1103/PhysRevD.90.014506.](#) [Phys.Rev. D90 \(2014\) 1, 014506.](#)

37 Publications in 2014-15

12) [Improved gradient flow for step scaling function and scale setting.](#)

By Anna Hasenfratz.

[arXiv:1501.07848 [hep-lat]].

13) [Targeting the Conformal Window: Scalars on the Lattice.](#)

By Evan Weinberg, Rich Brower, Anna Hasenfratz, Claudio Rebbi, Oliver Witzel.

[arXiv:1412.2148 [hep-lat]].

14) [Targeting the conformal window with 4+8 flavors.](#)

By Rich Brower, Anna Hasenfratz, Claudio Rebbi, Evan Weinberg, Oliver Witzel.

[arXiv:1411.3243 [hep-lat]].

15) [Nonperturbative beta function of eight-flavor SU\(3\) gauge theory.](#)

By Anna Hasenfratz, David Schaich, Aarti Veernala.

[arXiv:1410.5886 [hep-lat]].

16) [A novel approach to the study of conformality in the SU\(3\) theory with multiple flavors.](#)

By Richard Brower, Anna Hasenfratz, Claudio Rebbi, Evan Weinberg, Oliver Witzel.

[arXiv:1410.4091 [hep-lat]].

[10.1134/S1063776115030176.](#)

J.Exp.Theor.Phys. 120 (2015) 3, 423-427.

17) [Improving the continuum limit of gradient flow step scaling.](#)

By Anqi Cheng, Anna Hasenfratz, Yuzhi Liu, Gregory Petropoulos, David Schaich.

[arXiv:1404.0984 [hep-lat]].

[10.1007/JHEP05\(2014\)137.](#)

JHEP 1405 (2014) 137.

18) [Spectroscopy of SU\(4\) gauge theory with two flavors of sextet fermions.](#)

By Thomas DeGrand, Yuzhi Liu, Ethan T. Neil, Yigal Shamir, Benjamin Svetitsky.

[arXiv:1501.05665 [hep-lat]].

19) [Spectroscopy of SU\(4\) lattice gauge theory with fermions in the two index anti-symmetric representation.](#)

By Thomas DeGrand, Yuzhi Liu, Ethan T. Neil, Yigal Shamir, Benjamin Svetitsky.

[arXiv:1412.4851 [hep-lat]].

20) [Suppressing dislocations in normalized hypercubic smearing.](#)

By Thomas DeGrand, Yigal Shamir, Benjamin Svetitsky.

[arXiv:1407.4201 [hep-lat]].

[10.1103/PhysRevD.90.054501.](#)

Phys.Rev. D90 (2014) 5, 054501.

37 Publications in 2014-15

21) [Direct Detection of Stealth Dark Matter through Electromagnetic Polarizability.](#)

By Thomas Appelquist, Evan Berkowitz, Richard C. Brower, Michael I. Buchoff, George T. Fleming, Xiao-Yong Jin, Joe Kiskis, Graham D. Kribs et al..
[arXiv:1503.04205 [hep-ph]].

22) [Stealth Dark Matter: Dark scalar baryons through the Higgs portal.](#)

By Thomas Appelquist, Richard C. Brower, Michael I. Buchoff, George T. Fleming, Xiao-Yong Jin, Joe Kiskis, Graham D. Kribs, Ethan T. Neil et al..
[arXiv:1503.04203 [hep-ph]].

23) [Lattice simulations with eight flavors of domain wall fermions in SU\(3\) gauge theory.](#)

By LSD Collaboration (T. Appelquist et al.).

[arXiv:1405.4752 [hep-lat]].

[10.1103/PhysRevD.90.114502](https://doi.org/10.1103/PhysRevD.90.114502).

Phys.Rev. D90 (2014) 11, 114502.

24) [Maximum-Likelihood Approach to Topological Charge Fluctuations in Lattice Gauge Theory.](#)

By LSD Collaboration (R.C. Brower et al.).

[arXiv:1403.2761 [hep-lat]].

[10.1103/PhysRevD.90.014503](https://doi.org/10.1103/PhysRevD.90.014503).

Phys.Rev. D90 (2014) 1, 014503.

25) [Update of \$\langle V_{cb} \rangle\$ from the \$\langle \bar{B} \rightarrow D^* e \bar{\nu} \rangle\$ form factor at zero recoil with three-flavor lattice QCD.](#)

By Fermilab Lattice and MILC Collaborations (Jon A. Bailey et al.).

[arXiv:1403.0635 [hep-lat]].

[10.1103/PhysRevD.89.114504](https://doi.org/10.1103/PhysRevD.89.114504).

Phys.Rev. D89 (2014) 11, 114504.

26) [Composite bosonic baryon dark matter on the lattice: SU\(4\) baryon spectrum and the effective Higgs interaction.](#)

By Lattice Strong Dynamics (LSD) Collaboration (T. Appelquist et al.).

[arXiv:1402.6656 [hep-lat]].

[10.1103/PhysRevD.89.094508](https://doi.org/10.1103/PhysRevD.89.094508).

Phys.Rev. D89 (2014) 9, 094508.

27) [Improved Lattice Radial Quantization.](#)

By Richard C. Brower, Michael Cheng, George T. Fleming.

[arXiv:1407.7597 [hep-lat]].

28) [Improved Lattice Radial Quantization.](#)

By Richard C. Brower, Michael Cheng, George T. Fleming.

PoS LATTICE2013 (2014) 335.

37 Publications in 2014-15

29) [Dark nuclei. II. Nuclear spectroscopy in two-color QCD.](#)

By William Detmold, Matthew McCullough, Andrew Pochinsky.

[arXiv:1406.4116 [hep-lat]].

[10.1103/PhysRevD.90.114506](https://doi.org/10.1103/PhysRevD.90.114506).

Phys.Rev. D90 (2014) 11, 114506

30) [Dark Nuclei I: Cosmology and Indirect Detection.](#)

By William Detmold, Matthew McCullough, Andrew Pochinsky.

[arXiv:1406.2276 [hep-ph]].

[10.1103/PhysRevD.90.115013](https://doi.org/10.1103/PhysRevD.90.115013).

Phys.Rev. D90 (2014) 11, 115013.

31) [Lifting flat directions in lattice supersymmetry.](#)

By Simon Catterall, David Schaich.

[arXiv:1505.03135 [hep-lat]].

32) [Results from lattice simulations of \$N=4\$ supersymmetric Yang-Mills.](#)

By Simon Catterall, Joel Giedt, David Schaich, Poul H. Damgaard, Thomas DeGrand.

[arXiv:1411.0166 [hep-lat]].

PoS LATTICE2014 (2014) 267.

33) [Parallel software for lattice \$N=4\$ supersymmetric Yang-Mills theory.](#)

By David Schaich, Thomas DeGrand.

[arXiv:1410.6971 [hep-lat]].

[10.1016/j.cpc.2014.12.025](https://doi.org/10.1016/j.cpc.2014.12.025).

Comput.Phys.Commun. 190 (2015) 200-212.

34) [\$N=4\$ Supersymmetry on a Space-Time Lattice.](#)

By Simon Catterall, David Schaich, Poul H. Damgaard, Thomas DeGrand, Joel Giedt.

[arXiv:1405.0644 [hep-lat]].

[10.1103/PhysRevD.90.065013](https://doi.org/10.1103/PhysRevD.90.065013).

Phys.Rev. D90 (2014) 6, 065013.

35) [Conformality in twelve-flavour QCD.](#)

By Yasumichi Aoki, Tatsumi Aoyama, Ed Bennet, Masafumi Kurachi, Toshihide Maskawa, Kohtaroh Miura, Kei-ichi Nagai, Hiroshi Ohki et al..

[arXiv:1501.06660 [hep-lat]].

36) [Phase Structure Study of \$SU\(2\)\$ Lattice Gauge Theory with 8 Flavors.](#)

By Cynthia Y. -H. Huang, C. -J. David Lin, Kenji Ogawa, Hiroshi Ohki, Enrico Rinaldi.

[arXiv:1410.8698 [hep-lat]].

37) [Walking signals in \$N_f=8\$ QCD on the lattice.](#)

By Kei-ichi Nagai, Tatsumi Aoyama, Masafumi Kurachi, Toshihide Maskawa, Kohtaroh Miura, Kei-ichi Nagai, Hiroshi Ohki, Enrico Rinaldi et al..

PoS LATTICE2013 (2014) 071.